

# ON THE CHOICE NUMBER OF COMPLETE MULTIPARTITE GRAPHS WITH PART SIZE FOUR

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**ABSTRACT.** Let  $\text{ch}(G)$  denote the choice number of a graph  $G$ , and let  $K_{s*k}$  be the complete  $k$ -partite graph with  $s$  vertices in each part. Erdős, Rubin, and Taylor showed that  $\text{ch}(K_{2*k}) = k$ , and suggested the problem of determining the choice number of  $K_{s*k}$ . The first author established  $\text{ch}(K_{3*k}) = \lceil \frac{4k-1}{3} \rceil$ . Here we prove  $\text{ch}(K_{4*k}) = \lceil \frac{3k-1}{2} \rceil$ .

## 1. INTRODUCTION

Let  $G = (V, E)$  be a graph. A *list assignment*  $L$  for  $G$  is a function  $L : V \rightarrow 2^{\mathbb{N}}$ , where  $\mathbb{N}$  is the set of natural numbers and  $2^{\mathbb{N}}$  is the power set of  $\mathbb{N}$ . If  $|L(v)| = k$  for all vertices  $v \in V$ , then  $L$  is a  *$k$ -list assignment* for  $G$ . An  *$L$ -coloring*  $f$  from a list assignment  $L$  is a function  $f : V \rightarrow \mathbb{N}$  such that  $f(v) \in L(v)$  for all vertices  $v \in V$  and  $f(x) \neq f(y)$  whenever  $xy \in E$ .  $G$  is  *$L$ -colorable* if there exists an  $L$ -coloring of  $G$ ; it is  *$k$ -choosable* if it is  $L$ -choosable for all  $k$ -list assignments  $L$ . The *list chromatic number* or *choice number* of  $G$ , denoted  $\text{ch}(G)$ , is the smallest integer  $k$  such that  $G$  is  $k$ -choosable. The general list coloring problem may consider list assignments with uneven list sizes.

The study of list coloring was initiated by Vizing [13] and by Erdős, Rubin and Taylor [2]. It is a generalization of two well studied areas of combinatorics—graph coloring and transversal theory. Restricting the list assignment to a constant function, yields ordinary graph coloring; restricting the graph to a clique yields the problem of finding a system of distinct representatives (SDR) for the family of lists. Both restrictions play a role in this paper. Given the general nature of this parameter, it is hardly surprising that there are not many graphs whose exact choice number is known. However, there are some amazingly elegant results that add to the subject's charm. For example, Thomassen [12] proved that planar graphs have choice number at most 5, Voight [14] proved that this is tight, and Galvin [3] proved that line graphs of bipartite graphs have choice number equal to their clique number.

Erdős et al. [2] suggested determining the choice number of uniform complete multipartite graphs. More generally, let  $K_{1*k_1, 2*k_2, \dots}$  denote the complete multipartite graph with  $k_i$  parts of size  $i$ , where zero terms in the subscript are deleted. Since  $K_{1*k}$  is a clique and  $K_{s*1}$  is an independent set, these cases are trivial. Alon [1] proved the general bounds  $c_1 k \log s \leq \text{ch}(K_{s*k}) \leq c_2 k \log s$  for some constants  $c_1, c_2 > 0$ . This was tightened by Gazit and Krivelevich [4].

**Theorem 1** (Gazit and Krivelevich [4]).  $\text{ch}(K_{s*k}) = (1 + o(1)) \frac{\log s}{\log(1+1/k)}$ .

The next well-known example provides the best lower bounds for small values of  $s$ .

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**Example 2.**  $\text{ch}(K_{s*k}) \geq \lceil \frac{2(s-1)k-s+2}{s} \rceil$ : Let  $G = K_{s*k}$  have parts  $\{X_1, \dots, X_k\}$  with  $X_i = \{v_{i,1}, \dots, v_{i,s}\}$ . We will construct an  $(l-1)$ -list assignment  $L$  from which  $G$  cannot be colored. Equitably partition  $C := [2k-1]$  into  $s$  parts  $C_1, \dots, C_s$ . Define a list assignment  $L$  for  $G$  by  $L(v_{i,j}) = C \setminus C_j$ . Then each list has size at least

$$2k-1 - \left\lceil \frac{2k-1}{s} \right\rceil = \left\lfloor \frac{2ks-s-2k+1}{s} \right\rfloor = \left\lfloor \frac{2(s-1)k-2s+2}{s} \right\rfloor = l-1.$$

Consider any color  $\alpha \in C$ . Then  $\alpha \in C_i$  for some  $i \in [s]$ . So  $\alpha \notin L(x_{i,j})$  for every  $j \in [k]$ . Thus any  $L$ -coloring of  $G$  uses at least two colors for every part  $X_j$ . Since vertices in distinct parts are adjacent, they require distinct colors. As there are  $k$  parts this would require  $2k > |C|$  colors, which is impossible.

Restricting the question of Erdős et al., we ask for those integers  $s$  such that:

$$(1.1) \quad (\forall k \in \mathbb{Z}^+) \left[ \text{ch}(K_{s*k}) = l(s, k) := \left\lceil \frac{2(s-1)k-s+2}{s} \right\rceil \right].$$

The first two cases  $s = 2$  and  $s = 3$  have been solved:

**Theorem 3** (Erdős, Rubin and Taylor [2]). *All positive integers  $k$  satisfy  $\text{ch}(K_{2*k}) = k$ .*

**Theorem 4** (Kierstead [5]). *All positive integers  $k$  satisfy  $\text{ch}(K_{3*k}) = \lceil \frac{4k-1}{3} \rceil$ .*

Recently, Kozik, Micek, and Zhu [6] gave a very different proof of Theorem 4. The following more general result appears in [8].

**Theorem 5** (Ohba [8]).  $\text{ch}(K_{1*k_1, 3*k_3}) = \max\{k, \lceil \frac{n+k-1}{3} \rceil\}$ , where  $k = k_1 + k_3$  and  $n = k_1 + 3k_3$ .

The next example shows that the largest  $s$  satisfying (1.1) is at most 14.

**Example 6.** If  $k$  is even then  $\text{ch}(K_{15*k}) \geq l := 2k$ : Let  $G = K_{s*k}$  have parts  $\{X_1, \dots, X_k\}$  with  $X_i = \{v_{i,1}, \dots, v_{i,s}\}$ . We will construct an  $(l-1)$ -list assignment  $L$  from which  $G$  cannot be colored. Equitably partition  $C := [3k-1]$  into 6 parts  $C_1, \dots, C_6$ , and fix a bijection  $f : [15] \rightarrow \binom{[6]}{2}$ . Define a list assignment  $L$  for  $G$  by

$$L(v_{i,j}) = C \setminus \bigcup \{C_h : h \in f(i)\}.$$

Then each list has size at least

$$3k-1 - 2 \left\lceil \frac{3k-1}{6} \right\rceil = 2k-1 = l-1.$$

Consider any two colors  $\alpha, \beta \in C$ . Then  $\alpha, \beta \in \bigcup \{C_h : h \in f(i)\}$  for some  $i \in [15]$ . So  $\alpha, \beta \notin L(x_{i,j})$  for every  $j \in [k]$ . Thus any  $L$ -coloring of  $G$  uses at least three colors for every part  $X_j$ . Since  $3k > |C|$ , this is impossible.

Yang [15] proved  $\lceil \frac{3k}{2} \rceil \leq \text{ch}(K_{4*k}) \leq \lceil \frac{7k}{4} \rceil$ , and Noel et al. [7] improved the upper bound to  $\lceil \frac{5k-1}{3} \rceil$ . The main result of this paper is that (1.1) holds for  $s = 4$ . To prove this theorem we first extract a simple proof of Theorem 4 from [7], and then elaborate on it.

**Theorem 7.**  $\text{ch}(K_{4*k}) = l(4, k) := \lceil \frac{3k-1}{2} \rceil$ .

Some of the recent development of list coloring of complete multipartite graphs has been motivated by paintability, or on-line choosability. Introduced by Schauz [11], *paintability* is a coloring game played between two players Alice and Bob on a graph  $G = (V, E)$  and a function  $f : V \rightarrow \mathbb{N}$ . Let  $V_i$  denote the vertex set at the start of round  $i$ ; so  $V_1 = V$ . At

round  $i$ , Alice selects a nonempty set of vertices  $A_i \subseteq V_i$ , and Bob selects an independent set  $B_i \subseteq A_i$ . Then  $B_i$  is deleted from the graph so that  $V_{i+1} = V_i \setminus B_i$ , and the rounds are continued until  $V_n = \emptyset$ . Alice's goal is to present some vertex  $v$  more than  $f(v)$  times, while Bob's goal is to choose every vertex before it has been presented  $f(v) + 1$  times. We say that  $G$  is *on-line  $f$ -choosable* if player  $B$  has a strategy such that any vertex  $v \in V$  is in at most  $f(v)$  sets  $A_i$ , and *on-line  $k$  choosable* if  $G$  is on-line  $f$ -choosable when  $f(v) = k$  for all  $v \in V$ . The *on-line choice number*, denoted  $\text{ch}^{OL}(G)$ , is the least  $k$  such that  $G$  is on-line  $k$ -choosable.

This game formulation hides the on-line nature of the problem. Another way of thinking about it is that Alice has secretly assigned lists of colors to all the vertices. At round  $i$  she reveals all vertices whose list contains color  $i$ , and Bob colors an independent set of them with color  $i$ . In this formulation it is clear that  $\text{ch}(G) \leq \text{ch}^{OL}(G)$ .

Surprisingly, Schauz [11] proved that many results on choice number, including Brooks' theorem, Thomassen's theorem, and the Bondy-Boppana kernel lemma carry over to on-line choice number. It is unknown whether  $\text{ch}^{OL}(G) - \text{ch}(G)$  is bounded by a constant. Indeed, no graphs are known for which  $\text{ch}^{OL}(G) - \text{ch}(G) \geq 2$ . It is known that

$$\text{ch}(K_{2,2,3}) = 3 < 4 = \text{ch}^{OL}(K_{2,2,3}).$$

The explicit value of  $\text{ch}(K_{4*k})$  provided by Theorem 7 may be useful for establishing larger gaps. In Section 4 we show that  $\text{ch}(K_{4*3}) < \text{ch}^{OL}(K_{4*3})$ .

## 2. SET-UP

Fix  $s, k \in \mathbb{Z}^+$ . Let  $G = (V, E) = K_{s*k}$ , and  $\mathcal{P}$  be the partition of  $V$  into  $k$  independent  $s$ -sets. Let  $l = l(k, s) = \lceil \frac{(s-1)2k-s+2}{s} \rceil$ , and consider any  $l$ -list assignment  $L$  for  $G$ . Put  $C^* = \bigcup_{x \in V} L(x)$ . Let  $L - \alpha$  be the result of deleting  $\alpha$  from every list of  $L$ .

We may write  $x_1 \dots x_t$  for the subpart  $S = \{x_1, \dots, x_t\} \subseteq X \in \mathcal{P}$ ; when we use this notation we implicitly assume the  $x_i$  are distinct. Also set  $\bar{S} = X \setminus S$ . For a set of vertices  $S \subseteq V$  let  $\mathcal{L}(S) = \{L(x) : x \in S\}$ ,  $L(S) = \bigcap \mathcal{L}(S)$ ,  $W(S) = \bigcup \mathcal{L}(S)$ , and  $l(S) = |L(S)|$ . The operation of replacing the vertices in  $S$  by a new vertex  $v_S$  with the same neighborhood as  $S$  is called *merging*. The new vertex  $v_S$  is said to be *merged*; vertices that are not merged are called *original*. When merging a set  $S$  we also create a list  $L(v_S) = L(S)$ .

For a color  $\alpha \in C^*$ , let  $|X, \alpha| = |\{x \in X : \alpha \in L(x)\}|$  be the number of times  $\alpha$  appears in the lists of vertices of  $X$ ,  $N_i(X) = \{\alpha \in C^* : |X, \alpha| = i\}$  be the set of colors that appear exactly  $i$  times in the lists of vertices in  $X$ ,  $n_i(X) = |N_i(X)|$ , and  $N(X) = N_2(X) \cup N_3(X)$ . Let  $\sigma_i(X) = \sum \{l(I) : I \subseteq X \wedge |I| = i\}$  and  $\mu_i(X) = \max \{l(I) : I \subseteq X \wedge |I| = i\}$ .

For a set  $S$  and element  $x$  we use the notation  $S + x = S \cup \{x\}$  and  $S - x = S \setminus \{x\}$ .

The following lemma was proved independently by Kierstead [5], and by Reed and Sudakov [9], [10], and named by Rabern.

**Lemma 8** (Small Pot Lemma). *If  $\text{ch}(G) > r$  then there exists a list assignment  $L$  such that  $G$  has no  $L$ -coloring, all lists have size  $r$ , and their union has size less than  $|V(G)|$ .*

If  $s$  does not satisfy (1.1) then there is a minimal counterexample  $k$  with  $\text{ch}(K_{s,k}) > l(s, k)$ . By the Small Pot Lemma, this is witnessed by a list assignment  $L$  with  $|\bigcup \{L(x) : x \in V(G)\}| < |V|$ . We always assume  $L$  has this property.

**Lemma 9.** *Every part  $X$  of  $G$  satisfies  $L(X) = \emptyset$ .*

*Proof.* Otherwise there exists a list assignment  $L$ , a color  $\alpha$ , and a part  $X$  such that  $\alpha \in L(X)$ . Color each vertex in  $X$  with  $\alpha$ , set  $G' = G - X$ , and put  $L' = L - \alpha$ . Then  $L'$  witnesses that  $k - 1$  is a smaller counterexample, a contradiction.  $\square$

By Lemma 9,  $n_s(X) = 0$  for each part  $X \in \mathcal{P}$ . So by the Small Pot Lemma,  $|W(X)| = \sum_{i=1}^{s-1} n_i(X) < sk$ . Also  $\sum_{i=1}^{s-1} i n_i(X) = sl$  is the number of occurrences of colors in the lists of vertices of  $X$ . Thus

$$(2.1) \quad \sum_{i=2}^{s-1} (i-1)n_i(X) \geq sl - |W(X)| \geq s(l-k) + 1.$$

Now we warm-up by giving a short proof extracted from [7] of Theorem 4.

*Proof of Theorem 4.* Let  $s = 3$ ,  $l = l(3, k)$ , and assume  $G$  is a counterexample with  $k$  minimal. Then  $k > 1$ . By Lemma 9,  $n_3(X) = 0$  for all  $X \in \mathcal{P}$ . We obtain a contradiction by  $L$ -coloring  $G$ . First we use the following steps to partition  $V$  into sets of vertices that will receive the same color. Then we *merge* each set  $I$  into a single vertex  $v_I$ , and assign  $v_I$  the set of colors in  $L(I)$ . Finally we apply Hall's Theorem to choose a system of distinct representatives (SDR) for these new lists; this induces an  $L$ -coloring of  $G$ .

**Step 1.** Partition  $\mathcal{P}$  into a set  $\mathcal{R}$  of  $l - k$  *reserved* parts together with a set  $\mathcal{U} = \mathcal{P} \setminus \mathcal{R}$  of  $2k - l$  *unreserved* parts.

**Step 2.** Choose  $\mathcal{U}_1 \subseteq \mathcal{U}$  maximum subject to  $|\mathcal{U}_1| \leq \mu_2(X)$  for all  $X \in \mathcal{U}_1$ , and subject to this,  $\nu = \sum_{X \in \mathcal{U}_1} \mu_2(X)$  is maximum. Set  $u_1 = |\mathcal{U}_1|$ . For each  $X \in \mathcal{U}_1$  choose a pair  $I_X \subseteq X$  with  $l(I_X) \geq u_1$  maximum. Put  $\mathcal{U}_2 = \mathcal{U} \setminus \mathcal{U}_1$  and  $u_2 = |\mathcal{U}_2|$ . So

$$(2.2) \quad \text{if } u_1 < 2k - l \text{ then } \mu_2(X) \leq u_1 \text{ for all } X \in \mathcal{U}_2,$$

since otherwise we could increase  $\nu$  by adding  $X$  to  $\mathcal{U}_1$ , and deleting one part  $Y \in \mathcal{U}_1$  with  $\mu_2(Y) = u_1$ , if such a part  $Y$  exists.

**Step 3.** Using (2.1), each part  $X \in \mathcal{P}$  satisfies

$$n_2(X) \geq 3(l - k) + 1 \geq 3 \left\lceil \frac{k-1}{3} \right\rceil + 1 \geq k - 1 + 1 = k.$$

Form an SDR  $f$  for  $\{L(v_{I_X}) : X \in \mathcal{U}_1\} \cup \{N(X) : X \in \mathcal{R}\}$  by greedily choosing representatives for the first family and then for the second family. For each  $X \in \mathcal{R}$  choose a pair  $I_X \subseteq X$  so that  $f(x) \in L(I_X)$ .

**Step 4.** For each  $X \in \mathcal{U}_1 \cup \mathcal{R}$ , merge  $I_X$  to a new vertex  $v_{I_X}$ , let  $z_X \in X \setminus I_X$ , and set  $X' = \{v_{I_X}, z_X\}$ . If  $X \in \mathcal{U}_2$ , set  $X' = X$ . This yields a graph  $G'$  with parts  $\mathcal{P}' = \{X' : X \in \mathcal{P}\}$ , and list assignment  $L$ .

Next we use Hall's Theorem to prove that  $\{L(x) : x \in V(G')\}$  has an SDR. For this it suffices to prove:

$$(2.3) \quad |S| \leq \left| \bigcup \{L(x) : x \in S\} \right| \text{ for every } S \subseteq V(G').$$

To prove (2.3), let  $S \subseteq V(G')$  be arbitrary, and set  $W = W(S) := \bigcup \{L(x) : x \in S\}$ . We consider several cases in order, always assuming all previous cases fail.

**Case 1:** There exists  $X \in \mathcal{P}$  with  $|S \cap X'| = 3$ . Then  $|S| \leq 2k + u_2$ ,  $X' = X \in \mathcal{U}_2$  and  $u_2 \geq 1$ . Thus  $u_1 \leq 2k - l - u_2 < 2k - l$ , and so by (2.2),  $u_1 \geq \mu_2(X) \geq \sigma_2(X)/3$ . Using inclusion-exclusion, and Lemma 9,

$$\begin{aligned} |W| &\geq |W(X)| \geq \sigma_1(X) - \sigma_2(X) + \sigma_3(X) \geq 3l - 3u_1 = 3l - 3(2k - l - u_2) \\ &\geq 6(l - k) + 3u_2 \geq (2k - 2) + (2 + u_2) \geq 2k + u_2 \geq |S|. \end{aligned}$$

**Case 2:** There is  $X \in \mathcal{U}_2$  with  $|S \cap X'| = 2$ . Then  $X = X'$  and  $|S| \leq 2k$ . Since  $u_1 = 2k - l - u_2 < 2k - l$ , (2.2) yields

$$|W| \geq |W(S \cap X)| \geq 2l - l(S \cap X) \geq 2l - u_1 \geq 2l - (2k - l - u_2) \geq 3l + 1 - 2k = 2k \geq |S|.$$

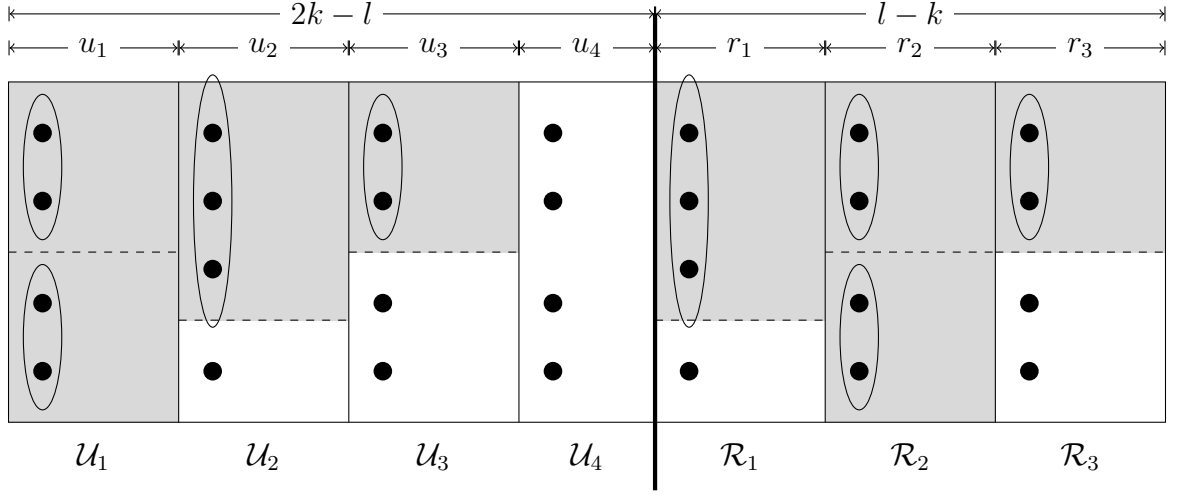


FIGURE 3.1. The partition  $\mathcal{P}'$  of  $K_{4*k}$ .

**Case 3:** There is  $X \in \mathcal{U}_1$  with  $|S \cap X'| = 2$ . As  $|S| \leq 2k - u_2 = l + u_1$  and  $L(v_{I_X} z_X) = L(X) = \emptyset$ ,

$$|W| \geq |W(S \cap X')| \geq l(v_{I_X}) + l(z_X) - l(v_{I_X} z_X) \geq u_1 + l \geq |S|.$$

**Case 4:**  $S$  has an original vertex. Then  $|S| \leq l \leq |W|$ .

**Case 5:** All vertices of  $S$  have been merged. Then  $|S| \leq |f(S)| \leq |W|$ .

□

### 3. THE MAIN THEOREM

In this section we prove our main result, Theorem 7. The case when  $k$  is odd is considerably more technical. Casual or first time readers may wish to avoid these additional details; the proof is organized so that this is possible. In particular, in the even case Step 11 and Lemmas 13 and 14 are not involved. We often use the partition  $k = (2k-l) + (l-k)$  of the integer  $k$ , and note that  $2k-l = l-k+b$ , where  $b = k \bmod 2$ .

*Proof of Theorem 7.* Our set-up is the same as in the proof of Theorem 4. Let  $s = 4$ ,  $l = l(4, k)$ , and  $G = K_{4*k}$ . The theorem is trivial if  $k = 1$ . Let  $k > 1$  be a minimal counterexample, and let  $L$  be an  $l$ -list assignment for  $G$  with  $|W(V)| \leq 4k - 1$  and  $L(X) = \emptyset$  for all parts  $X \in \mathcal{P}$ . Again we partition  $V$  into sets of vertices that will receive the same color, and then find an SDR for the induced list assignment that in turn induces an  $L$ -coloring of  $G$ . See Figure 3.1.

**Step 1.** Partition  $V$  as  $\mathcal{P} = \mathcal{U} \cup \mathcal{R}$ , where  $|\mathcal{R}| = l - k$ ,  $|\mathcal{U}| = 2k - l$ ,  $\mathcal{R} = \mathcal{R}_1 \cup \mathcal{R}_2 \cup \mathcal{R}_3$  and  $\mathcal{U} = \mathcal{U}_1 \cup \mathcal{U}_2 \cup \mathcal{U}_3 \cup \mathcal{U}_4$  as follows.

**Step 2.** Choose  $\mathcal{U}_1 \subseteq \mathcal{P}$  maximum subject to  $|\mathcal{U}_1| \leq 2k - l$  and for every  $X \in \mathcal{U}_1$  there is a pair  $I_X \subseteq X$  with  $l(I_X), l(\bar{I}_X) \geq k$ . Put  $\mathcal{U}_1 \subseteq \mathcal{U}$ , and let  $u_1 := |\mathcal{U}_1|$ . Then:

$$(3.1) \quad \text{If } u_1 < 2k - l \text{ then } (\forall X \in \mathcal{P} \setminus \mathcal{U}_1)(\forall I \subseteq X)[|I| = 2 \rightarrow \min\{l(I), l(\bar{I})\} \leq k - 1].$$

**Step 3.** Choose  $\mathcal{U}_2 \subseteq \mathcal{P} \setminus \mathcal{U}_1$  maximum subject to  $|\mathcal{U}_2| \leq 2k - l - u_1$  and  $|\mathcal{U}_2| \leq \mu_3(X)$  for all  $X \in \mathcal{U}_2$ ; subject to this let  $\nu = \sum_{X \in \mathcal{U}_2} \mu_3(X)$  be maximum. Put  $\mathcal{U}_2 \subseteq \mathcal{U}$ , and let  $u_2 = |\mathcal{U}_2|$ . If  $\mathcal{U}_2 \neq \emptyset$  then let  $\dot{Z} \in \mathcal{U}_2$ ; else  $\dot{Z} = \emptyset$ . For each  $X \in \mathcal{U}_2$  choose a triple  $I_X \subseteq X$  with  $l(I_X) \geq u_2$  maximum. Since  $\nu$  cannot be increased:

$$(3.2) \quad \text{If } u_1 + u_2 < 2k - l \text{ then } (\forall X \in \mathcal{U}_3 \cup \mathcal{U}_4 \cup \mathcal{R})[\mu_3(X) \leq u_2].$$

**Step 4.** Choose  $\mathcal{R}_1 \subseteq \mathcal{P} \setminus (\mathcal{U}_1 \cup \mathcal{U}_2)$  maximum subject to  $|\mathcal{R}_1| \leq l - k$  and for all  $X \in \mathcal{R}_1$  there exists  $I_X \subseteq X$  with  $|I_X| = 3$  such that there is an SDR  $f_1$  of  $\mathcal{L}(M_1)$ , where  $M_1 := \{v_{I_X} : X \in \mathcal{U}_2 \cup \mathcal{R}_1\}$ ; let  $C_1 = \text{ran}(f_1)$ . Put  $\mathcal{R}_1 \subseteq \mathcal{R}$ , and let  $r_1 := |\mathcal{R}_1|$ . Then:

$$(3.3) \quad \text{If } r_1 < l - k \text{ then } (\forall X \in \mathcal{U}_3 \cup \mathcal{U}_4 \cup \mathcal{R}_2 \cup \mathcal{R}_3)[N_3(X) \subseteq C_1].$$

**Step 5.** Choose  $\mathcal{U}_3 \subseteq \mathcal{P} \setminus (\mathcal{U}_1 \cup \mathcal{U}_2 \cup \mathcal{R}_1)$  maximum subject to  $|\mathcal{U}_3| \leq 2k - l - u_1 - u_2$  and  $l - k + u_2 + |\mathcal{U}_3| \leq \mu_2(X)$  for all  $X \in \mathcal{U}_3$ ; subject to this let  $\nu = \sum_{X \in \mathcal{U}_3} \mu_2(X)$  be maximum. Put  $\mathcal{U}_3 \subseteq \mathcal{U}$ , and  $u_3 = |\mathcal{U}_3|$ . Since  $\nu$  cannot be increased:

$$(3.4) \quad \text{If } u_1 + u_2 + u_3 < 2k - l \text{ then } (\forall X \in \mathcal{U}_4 \cup \mathcal{R}_2 \cup \mathcal{R}_3)[\mu_2(X) \leq l - k + u_2 + u_3].$$

For all  $X \in \mathcal{U}_3$  choose a pair  $I_X = xy \subseteq X$  with  $l(I_X) \geq l - k + u_2 + u_3$  maximum; subject to this choose  $I_X$  so that  $\Delta_1(I_X) := l(I_X) - l(\bar{I}_X)$  is maximum. Set  $\Delta_2(I_X) := 2u_2 - l(xyz) - l(xyw)$ , where  $zw = \bar{I}_X$ . Using  $r_1 \leq l - k$ , extend  $f_1$  to an SDR  $f_2$  of  $\mathcal{L}(M_2)$ , where  $M_2 := M_1 \cup \{v_{I_X} : X \in \mathcal{U}_3\}$ ; set  $C_2 = \text{ran}(f_2)$ .

**Step 6.** Choose  $\mathcal{R}_2 \subseteq \mathcal{P} \setminus (\mathcal{U}_1 \cup \mathcal{U}_2 \cup \mathcal{U}_3 \cup \mathcal{R}_1)$  maximum subject to  $|\mathcal{R}_2| \leq l - k - r_1$  and  $\sigma_2(X) - \sigma_3(X) \geq 5(l - k) + 2u_1 + 2u_2 + u_3 + r_1 + |\mathcal{R}_2|$  for all  $X \in \mathcal{R}_2$ ; subject to this let  $\sum_{X \in \mathcal{R}_2} \sigma_2(X) - \sigma_3(X)$  be maximum. Put  $\mathcal{R}_2 \subseteq \mathcal{R}$ , and set  $r_2 = |\mathcal{R}_2|$ . Then:

$$\text{If } r_1 + r_2 < l - k \text{ then } (\forall X \in \mathcal{U}_4 \cup \mathcal{R}_3)$$

$$(3.5) \quad [\sigma_2(X) - \sigma_3(X) \leq 5(l - k) + 2u_1 + 2u_2 + u_3 + r_1 + r_2].$$

**Step 7.** Choose  $\mathcal{R}_3 \subseteq \mathcal{P} \setminus (\mathcal{U}_1 \cup \mathcal{U}_2 \cup \mathcal{U}_3 \cup \mathcal{R}_1 \cup \mathcal{R}_2)$  with  $|\mathcal{R}_3| = l - k - r_1 - r_2$ , and set  $\mathcal{R} = \mathcal{R}_1 \cup \mathcal{R}_2 \cup \mathcal{R}_3$ . Let  $r_3 = |\mathcal{R}_3|$ . For  $I \subseteq X$ , put  $L'(I) = L(I) \setminus C_2$  and  $l'(I) = |L'(I)|$ . Using Lemma 11, for all  $X \in \mathcal{R}_3$  there exists a pair  $I_X \subseteq X$  with  $l'(\bar{I}_X) \leq l'(I_X)$  such that  $f_2$  can be extended to an SDR  $f_3$  of  $\mathcal{L}(M_3)$ , where  $M_3 := M_2 \cup \{v_{I_X} : X \in \mathcal{R}_3\}$ . Let  $C_3 = \text{ran}(f_3)$ .

**Step 8.** Put  $\mathcal{U} = \mathcal{P} \setminus \mathcal{R}$ ,  $\mathcal{U}_4 := \mathcal{U} \setminus (\mathcal{U}_1 \cup \mathcal{U}_2 \cup \mathcal{U}_3)$ , and  $u_4 := |\mathcal{U}_4|$ .

**Step 9.** Using Lemma 12, choose a pair  $I_X \subseteq X$  for all  $X \in \mathcal{R}_2$  so that  $\mathcal{L}(M_4)$  has an SDR  $f_4$  extending  $f_3$ , where  $M_4 := M_3 \cup \{v_{I_X}, v_{\bar{I}_X} : X \in \mathcal{U}_1 \cup \mathcal{R}_2\}$ .

**Step 10.** Let  $G' := (V', E')$  be the graph obtained from  $G$  by merging each  $I_X$  with  $X \in \mathcal{U}_2 \cup \mathcal{U}_3 \cup \mathcal{U}_1 \cup \mathcal{R}_1 \cup \mathcal{R}_2 \cup \mathcal{R}_3$  and each  $\bar{I}_X$  with  $X \in \mathcal{U}_1 \cup \mathcal{R}_2$ . For a part  $X$ , let  $X'$  be the corresponding part in  $G'$ , and set  $\mathcal{P}' = \{X' : X \in \mathcal{P}\}$ .

**Step 11.** Set  $0 = \dot{u} = \dot{r} = \ddot{u}$ . If  $k$  is odd ( $b = 1$ ) then we merge one more pair of vertices under any of the following special circumstances:

- (a) there exists  $X \in \mathcal{U}_4$  with  $|W(X)| < |G'|$ . Fix such an  $X = \dot{X}$ . By Lemma 13,  $r_3 = 0$  and there is a pair  $\dot{I} \subseteq \dot{X}$  such that (i)  $f_4$  can be extended to an SDR  $f$  of  $\mathcal{L}(M)$ , where  $M := M_4 + v_{\dot{I}}$ ; (ii)  $|W(\{v_{\dot{I}}, v\})| \geq 2k - 1$ , and if equality holds then  $|W(\{v_{\dot{I}}, v\} \cup \dot{Z}') \cup C_4| \geq 2k$  for both  $v \in \bar{\dot{I}}$ ; and (iii)  $W(\bar{\dot{I}} + v_{\dot{I}}) \geq |G'| - 1$ . Merge  $\dot{I}$  and set  $\dot{u} = 1$ .
- (b)  $u_1 = r_2 = 0$  and there is  $Y \in \mathcal{R}_3$  with  $|W(Y)| \leq 3k - 1 - u_2 - r_1$ . Then (a) fails since  $r_3 \geq 1$ . Fix such a  $Y = \dot{Y}$ . As  $u_1 = 0 = r_2$ ,  $M_4 = M_3$ . Since  $r_3 \neq 0$ , (a) is not executed. By Lemma 11,  $f_3$  can be chosen so that it is an SDR of  $\mathcal{L}(M)$ , where  $M := M_4 + v_{\bar{\dot{Y}}}$ . Merge  $\bar{\dot{Y}}$  and set  $\dot{r} = 1$ .
- (c) condition (a) fails and there exist  $X \in \mathcal{U}_4$  and  $xyz \subseteq X$  with

$$|W(xyz \cup \dot{Z}')| \leq 2k + u_4 - 1 < |W(X)|.$$

Fix such an  $X = xyzw = \ddot{X}$ . By Lemma 14 there is a pair  $\ddot{I} \subseteq xyz$  such that (i)  $f_4$  can be extended to an SDR  $f$  of  $\mathcal{L}(M)$ , where  $M := M_4 + v_{\ddot{I}}$ ; (ii)  $|W(\{v_{\ddot{I}}, v\})| \geq 2k$

for  $v \in xyz \setminus \dot{I}$  and  $|W(\{v_{\dot{I}}, w\})| \geq 2k - 1$ ; and (iii)  $|W(\bar{\dot{I}} + v_{\dot{I}})| \geq 2k + u_4$ . Merge  $I_{\dot{X}} := \dot{I}$  and set  $\dot{u} = 1$ .

**Step 12.** Recall that  $G'$  is the graph obtained after the first ten steps. Let  $H$  be the final graph obtained by this merging procedure. (If  $b = 0$ , and possibly otherwise,  $H = G'$ ). Also let  $M$  be the final set of merged vertices,  $f$  be the final SDR of  $\mathcal{L}(M)$ , and  $C = \text{ran}(f)$ .

Our next task is to state and prove the four lemmas on which the algorithm is based. We will need the following easy claim.

**Claim 10.** Let  $\mathcal{P}_1, \mathcal{P}_2, \mathcal{P}_3$  be the three partitions of a 4-set  $X$  into pairs. For all  $I_1 \in \mathcal{P}_1, I_2 \in \mathcal{P}_2, I_3 \in \mathcal{P}_3$  there exists  $v \in X$  such that either (i)  $v \in I_1 \cap I_2 \cap I_3$  or (ii)  $v \notin I_1 \cup I_2 \cup I_3$ .

**Lemma 11.** *There is a family  $\mathcal{I} = \{I_X : X \in \mathcal{R}_3\}$  such that  $I_X \subseteq X$ ,  $|I_X| = 2$ ,  $l'(I_X) \geq l'(\bar{I}_X)$ , and  $\mathcal{L}(M_2 \cup \{v_{I_X} : X \in \mathcal{R}_3\})$  has an SDR  $f_3$  extending  $f_2$ .*

*Furthermore, if  $u_1 = 0 = r_2$  and there is  $\dot{Y} \in \mathcal{R}_3$  with  $|W(\dot{Y})| \leq 3k - 1 - u_2 - r_1$ , then  $I_{\dot{Y}}$  can be chosen so that there is an SDR  $f$  of  $\mathcal{L}(M)$  extending  $f_2$ , where  $M = M_3 + v_{\bar{I}_{\dot{Y}}}$ .*

*Proof.* Consider any  $X \in \mathcal{R}_3$ , and let  $A(X) = N_2(X) \setminus C_2$  be the set of colors available for coloring a pair of vertices from  $X$ . Then  $L'(I) = L(I) \cap A(X)$  for all pairs  $I \subseteq X$ . For each color  $\alpha \in A$ , set  $I(\alpha) = \{x \in X : \alpha \in L(x)\}$ . As  $A(X) \subseteq N_2(X)$ ,  $|I(\alpha)| = 2$ . Let  $B(X) = \{\alpha \in A(X) : l'(I(\alpha)) \geq l'(\bar{I}(\alpha))\}$ . For the first part, it suffices to show that  $\mathcal{B} = \{B(Z) : Z \in \mathcal{R}_3\}$  has an SDR  $g$ : for each  $X \in \mathcal{R}_3$  set  $I_X = I(\alpha)$ , and  $f(v_{I_X}) = \alpha$ , where  $\alpha = g(B(X))$ .

By (3.3),  $N_3(X) \subseteq C_1 \subseteq C_2$ ; so  $n_3(X) \leq u_2 + r_1$ . By (2.1)

$$(3.6) \quad n_2(X) + 2n_3(X) \geq 4l - |W(X)| \geq 4(l - k) + 1 \geq 2k - 1.$$

Thus

$$(3.7) \quad \begin{aligned} |A(X)| &= n_2(X) + n_3(X) - |C_2| \geq n_2(X) + 2n_3(X) - n_3(X) - |C_2| \\ &\geq 2k - 1 - (2u_2 + u_3 + 2r_1) \geq 2r_3 - 1. \end{aligned}$$

If  $\alpha \in A(X) \setminus B(X)$  then  $A(X) \cap L(\bar{I}(\alpha)) \subseteq B(X)$ . So  $|B(X)| \geq \lceil |A(X)|/2 \rceil \geq r_3$ . Hence  $\mathcal{B}$  has an SDR  $g$ .

Now suppose  $\dot{Y}$  is defined in Step 11(b). Then  $b = 1$ ,  $u_1 = r_2 = 0$ , and  $|W(\dot{Y})| \leq 3k - 1 - u_2 - r_1$ . As  $b = 1$ ,  $k$  is odd; so  $k \geq 3$ . If  $r_3 \geq 2$  then fix  $Z \in \mathcal{R}_3 - \dot{Y}$ . A partition  $\mathcal{Q} = \{I, \bar{I}\}$  of  $\dot{Y}$  into pairs is *bad* if  $l'(I) = 0$  or  $l'(\bar{I}) = 0$ ; else it is *good*. It is *weak* if  $r_3 \geq 2$ ,  $L'(I) \cup L'(\bar{I}) \subseteq B(Z)$  and  $|B(Z)| = r_3$ ; else it is *strong*.

For the second part, it suffices to show that  $\dot{Y}$  has a good, strong partition: If  $\{\dot{I}, \bar{\dot{I}}\}$  is a good, strong partition then choose  $\alpha, \beta \in L'(I) \cup L'(\bar{I})$  with  $|B(Z) - \alpha| \geq r_3$  and  $\alpha \in L'(I)$  iff  $\beta \in L'(\bar{I})$ . Then  $\alpha$  and  $\beta$  are the representatives for  $L'(I)$  and  $L'(\bar{I})$ , or *vice versa*. We are done if  $r_3 = 1$ . If  $r_3 \geq 2$  then continue by greedily choosing an SDR of  $\mathcal{B} - B(\dot{Y}) - B(Z) + (B(Z) - \alpha) + L'(I) + L'(\bar{I})$  by picking representatives for  $\mathcal{B} - B(\dot{Y}) - B(Z)$ , and finally picking a representative for  $B(Z) - \alpha$ .

Using the first half of (3.6),

$$n_2(\dot{Y}) + 2n_3(\dot{Y}) \geq 4l - |W(\dot{Y})| \geq 2l + u_2 + r_1.$$

So by (3.7),

$$|A(\dot{Y})| \geq 2l + u_2 + r_1 - (2u_2 + u_3 + 2r_1) \geq 2l - u_2 - u_3 - r_1 \geq 2k + r_3 - 1.$$

First suppose for a contradiction that  $\dot{Y}$  has no good partition. For each partition  $\mathcal{P}$  of  $X$  into pairs, choose  $I \in \mathcal{P}$  with  $L(I) \cap A(\dot{Y}) = \emptyset$ . Using Claim 10, there exists  $w \in \dot{Y}$  such that either (i)  $L(wx) \cap A(\dot{Y}) = \emptyset$  for all  $x \in \dot{Y} \setminus w$  or (ii)  $L(xy) \cap A(\dot{Y}) = \emptyset$  for all  $xy \subseteq \dot{Y} \setminus w$ . If (i) holds then  $L(w) \cap A(\dot{Y}) = \emptyset$ . This yields the contradiction

$$l + 2k + r_3 - 1 \leq l(w) + |A(\dot{Y})| \leq |W(\dot{Y})| \leq 3k - 1 - u_2 - r_1 < l + 2k - 1.$$

If (ii) holds then  $A(\dot{Y}) \subseteq L(w)$ , and so  $l < |A(\dot{Y})| \leq l(w)$ , another contradiction.

So  $\dot{Y}$  has a good partition (say)  $\mathcal{Q}_1 = \{xy, zw\}$ . Suppose  $\mathcal{Q}_1$  is weak. Then  $r_3 \geq 2$  and  $|A_0| \geq 2k - 1$ , where  $A_0 := A(\dot{Y}) \setminus B(Z) \subseteq A(\dot{Y}) \setminus (L'(xy) \cup L'(zw))$ . The former implies  $2 \leq r_3 \leq l - k \leq 2k - l$ ; so (\*)  $l \leq 2k - 2$ . If the other two partitions of  $\dot{Y}$  are both bad then there is  $v \in \dot{Y}$  with  $A_0 \subseteq L(v)$ . So  $2k - 1 \leq |A_0| \leq l$  contradicting (\*). Say  $\mathcal{Q}_2 = \{xw, yz\}$  is good. If  $\mathcal{Q}_2$  is weak then  $A_0 \subseteq A(\dot{Y}) \setminus (L'(xy) \cup L'(zw) \cup L'(xw) \cup L'(yz))$ . Then  $|L'(xz) \cup L'(yw)| \geq 2k - 1$ . So  $\mathcal{Q}_3 = \{xz, yw\}$  is strong. By (\*),  $l'(xz), l'(yw) \leq l < 2k - 1$ . Thus  $l'(xz), l'(yw) \geq 1$ , and so  $\mathcal{Q}_3$  is also good.  $\square$

**Lemma 12.** *For each  $X \in \mathcal{R}_2$  there is a pair  $I_X \subseteq X$  such that  $\{L(I_X) : X \in \mathcal{P} \setminus \mathcal{U}_4\} \cup \{L(\bar{I}_X) : X \in \mathcal{U}_1 \cup \mathcal{R}_2\}$  has an SDR  $f_4$  that extends  $f_3$ .*

*Proof.* Each  $X \in \mathcal{U}_1$  satisfies  $L(I_X), L(\bar{I}_X) \geq k$ . Thus  $|L(I_X) \setminus C_3|, |L(\bar{I}_X) \setminus C_3| \geq k - u_2 - u_3 - r_1 - r_3 \geq u_1$ . By Theorem 3,  $\{L(I_X) \setminus C_3, L(\bar{I}_X) \setminus C_3 : X \in \mathcal{U}_1\}$  has an SDR, and so  $f_3$  can be extended to an SDR  $g$  for  $\mathcal{L}(M'_3)$ , where  $M'_3 := M_3 \cup \{I_X, \bar{I}_X : X \in \mathcal{U}_1\}$ . Let  $C^g = \text{ran}(g)$ . Then  $|C^g| = 2u_1 + u_2 + u_3 + r_1 + r_3$ . Consider any  $X = xyzw \in \mathcal{R}_2$ . Let  $A(X) = N_2(X) \setminus C^g$ . Again by Theorem 3 it suffices to show:

$$(3.8) \quad (\exists I_X \subseteq X)[|I_X| = 2 \wedge |L(I_X) \cap A(X)| \geq r_2 \wedge |L(\bar{I}_X) \cap A(X)| \geq r_2].$$

Observe  $\sigma_2(X) = n_2(X) + 3n_3(X)$  and  $\sigma_3(X) = n_3(X)$ . So  $n(X) = n_2(X) + n_3(X) = \sigma_2(X) - 2\sigma_3(X)$ . By (3.3),  $N_3(X) \subseteq C^g$ , and by (3.4)  $\sigma_3(X) \leq u_2 + r_1$ . So

$$(3.9) \quad \begin{aligned} n(X) &= \sigma_2(X) - 2\sigma_3(X) \geq 5(l - k) + 2u_1 + 2u_2 + u_3 + r_1 + r_2 - (u_2 + r_1) \\ &\geq 5(l - k) + 2u_1 + u_2 + u_3 + r_2 \text{ and} \end{aligned}$$

$$(3.10) \quad \begin{aligned} |A(X)| &= |N_2(X) \setminus C^g| = |N_2(X) \cup N_3(X) \setminus C^g| = n(X) - |C^g| \\ &\geq 5(l - k) + 2u_1 + u_2 + u_3 + r_2 - (2u_1 + u_2 + u_3 + r_1 + r_3) \\ &\geq 5(l - k) - r_1 + r_2 - r_3 \geq 4(l - k) + 2r_2. \end{aligned}$$

Suppose (3.8) fails. Then for each of the three partitions of  $X$  into pairs, there is a pair  $uv$  with  $|L(uv) \cap A(X)| \leq r_2 - 1$ . Using Claim 10, there exists  $v \in X$  such that either (i)  $|L(vw) \cap A(X)| \leq r_2 - 1$  for all  $w \in X - v$  or (ii)  $|L(vw) \cap A(X)| \leq r_2 - 1$  for all  $w \in X - v$ .

If (i) holds then

$$|L(v) \cap N(X)| \leq |C^g| + \sum_{w \in X - v} |L(vw) \cap A(X)| \leq |C^g| + 3r_2 - 3.$$

Since  $|L(w) \cap N(X)| \leq l$  for all  $w \in X - v$ ,

$$2n(X) \leq \sum_{v \in X} |L(v) \cap N(X)| \leq 3l + (|C^g| + 3r_2 - 3).$$

Using  $|C^g| = 2u_1 + u_2 + u_3 + r_1 + r_3$  and (3.9) implies

$$(3.11) \quad \begin{aligned} 10(l - k) + 4u_1 + 2u_2 + 2u_3 + 2r_2 &\leq 3l - 2u_1 + u_2 + u_3 + r_1 + r_3 + 3r_2 - 3 \\ 4l - k + (6l - 9k + 3) + 2u_1 + u_2 + u_3 &\leq 3l + r_1 + r_2 + r_3 \leq 4l - k. \end{aligned}$$



Since  $6l - 9k = -3b$ , both  $b = 1$  and  $0 = u_1 = u_2 = u_3$ . Now, by (3.4),  $\mu_2(X) \leq l - k$ . So  $|L(w) \cap N(X)| \leq 3(l - k)$  for all  $w \in X$ . Strengthening the estimate in (3.11) yields the contradiction:

$$\begin{aligned} 10(l - k) + 2r_2 &\leq 9(l - k) + (|C^g| + 3r_2 - 3) \\ l - k &\leq r_1 + r_2 + r_3 - 3 < l - k. \end{aligned}$$

Thus (ii) holds. So

$$(3.12) \quad |A(X)| \leq l(v) + \sum_{wx \subseteq X-v} |L(uv) \cap A(X)| \leq l + 3(r_2 - 1).$$

Using (3.10), (3.12) and  $2l - 3k = -b$ , this yields the contradiction

$$\begin{aligned} 4(l - k) + 2r_2 \leq |A(X)| &\leq l + 3(r_2 - 1) \\ l - k + 2 \leq 3l - 4k + 3 &\leq r_2 \leq l - k. \end{aligned}$$

□

**Lemma 13.** Suppose  $X = xyzw \in \mathcal{U}_4$  and  $|W(X)| < |G'|$ . Then  $b = 1$ ,  $u_1 = 0 = r_3$ ,  $u_2 + u_3 \geq 1$ , and there exists a pair  $J \subseteq X$  such that:

- (1)  $L(J) \not\subseteq C_4$ ;
- (2)  $|W(\{v_J, v\})| \geq 2k - 1$  and if  $|W(\{v_J, v\})| = 2k - 1$  then  $|W(\{v_J, v\} \cup \bar{Z}) \cup C_4| \geq 2k$  for both  $v \in \bar{J}$ ;
- (3)  $|W(\bar{J} + v_J)| \geq |G'| - 1$ ; in particular  $|W(X)| \geq |G'| - 1$ .

*Proof.* Now  $|G'| = 3k - u_1 - u_2 + u_4 - r_1 - r_2$ . Observe that

$$(3.13) \quad \sigma_2(X) - \sigma_3(X) \geq 5(l - k) + 2u_1 + 2u_2 + u_3 + r_1 + r_2 + 1,$$

since otherwise inclusion-exclusion yields the contradiction:

$$\begin{aligned} |W(X)| &= \sigma_1(X) - \sigma_2(X) + \sigma_3(X) \\ &\geq 4l - 5(l - k) - 2u_1 - 2u_2 - u_3 - r_1 - r_2 \\ &\geq 3k + (2k - l - u_1 - u_2 - u_3) - u_1 - u_2 - r_1 - r_2 \\ &\geq 3k - u_1 - u_2 + u_4 - r_1 - r_2 = |G'| > |W(X)|. \end{aligned}$$

By (3.13) and (3.5),  $r_1 + r_2 = l - k$  and  $r_3 = 0$ . Consider any pair  $I = xy \subseteq X$ . Then

$$(3.14) \quad \begin{aligned} |W(\bar{I} + v_I)| &\geq l(xy) + l(z) + l(w) - l(xyz) - l(xyw) - l(zw) \\ &\geq 2l - 2u_2 + \Delta_1(I) + \Delta_2(I) \end{aligned}$$

$$(3.15) \quad |G'| - |W(\bar{I} + v_I)| \leq b - 2u_1 + (u_1 + u_2 + u_4 - l + k) - \Delta_1(I) - \Delta_2(I)$$

$$(3.16) \quad 1 \leq 2b - 2u_1 - u_3 - \Delta_1(I) - \Delta_2(I).$$

By (3.16),  $\Delta_1(I) + \Delta_2(I) \leq 1$ . As  $\Delta_1(I) = -\Delta_1(\bar{I})$  and  $\Delta_2(I), \Delta_2(\bar{I}) \geq 0$ , we could choose  $I$  with  $\Delta_1(I) + \Delta_2(I) \geq 0$ . So  $b = 1$ ,  $u_1 = 0$ ,  $u_3 \leq 1$ , and

$$(3.17) \quad 1 \leq |G| - |W(\bar{I} + v_I)| \leq 2 - u_3 - \Delta_1(I) - \Delta_2(I) \leq 2.$$

Furthermore, using  $\Delta_1(I) = -\Delta_1(\bar{I})$  again,

$$(3.18) \quad 0 \leq 4u_2 - \sigma_3(X) = \Delta_2(I) + \Delta_2(\bar{I}) = \Delta_1(I) + \Delta_2(I) + \Delta_1(\bar{I}) + \Delta_2(\bar{I}) \leq 2.$$

By (3.13),  $r_1 + r_2 = l - k$ ,  $\sigma_2(X) \leq 6\mu_2(X)$ , (3.4), and  $\sigma_3 = 4u_2 - \Delta_2(I) - \Delta_2(\bar{I})$ ,

$$(3.19) \quad 1 + 6(l - k) + 2u_2 + u_3 + \sigma_3(X) \leq \sigma_2(X) \leq 6(l - k + u_2 + u_3)$$

$$(3.20) \quad 1 + u_3 + 6(l - k + u_2) - \Delta_2(I) - \Delta_2(\bar{I}) \leq \sigma_2(X) \leq 6(l - k + u_2 + u_3).$$

By (3.19)  $u_2 + u_3 \geq 1$ . So the first three assertions of the lemma have been proved. It remains to find a pair  $J \subseteq X$  satisfying (1–3).

First suppose  $u_3 = 1$ . By (3.17),  $\Delta_1(I) + \Delta_2(I) = 0$  for all pairs  $I \subseteq X$ . So  $\Delta_1(I) \leq 0$  and  $\Delta_1(\bar{I}) \leq 0$ . As  $\Delta_1(I) = -\Delta_1(\bar{I})$ , this implies  $\Delta_1(I) = 0 = \Delta_1(\bar{I})$ . So  $\Delta_2(I) = 0 = \Delta_2(\bar{I})$ . By (3.20), there exists a pair  $I \subseteq X$  with  $l(I) = l - k + u_2 + u_3$ . As  $\Delta_1(I) = 0$ ,  $l(\bar{I}) = l - k + u_2 + u_3$ . Thus

$$|W(\{v_I, v_{\bar{I}}\})| = l(I) + l(\bar{I}) = 2(l - k + u_2 + u_3) > 2(l - k) + u_2 + u_3 \geq |C_4|.$$

Pick  $J \in \{I, \bar{I}\}$  such that  $L(J) \not\subseteq C_4$ . Then (1) holds. For (2), let  $v' \in \bar{J}$ , and observe

$$|W(\{v_J, v'\})| = l(J) + l(v') - l(J + v') \geq 2l - k + u_2 + u_3 - u_2 = 2k.$$

Thus (2) holds. As  $u_3 = 1$ , (3.17) implies (3).

Otherwise  $u_3 = 0$ . Then  $u_2 \geq 1$ , and so  $\dot{Z}$  is defined in Step 3. Put  $C_0 := C_4 \cup W(\dot{Z}')$ . By Step 3,  $|C_0| \geq |W(\dot{Z}')| \geq l + u_2$ . Call a vertex  $x \in X$  *bad* if  $|L(x) \cup C_0| \leq 2k - 1$ ; otherwise  $x$  is *good*. If  $x$  is bad then  $|C_0 \setminus L(x)| \leq 2k - 1 - l \leq l - k$ . If another vertex  $y$  is also bad, then using (3.4) and (3.17),

$$\begin{aligned} l - k + u_2 \geq l(xy) &\geq |L(xy) \cap C_0| \geq |C_0| - |C_0 \setminus L(x)| - |C_0 \setminus L(y)| \\ &\geq l + u_2 - 2(l - k) \geq l - k + u_2 + 1, \end{aligned}$$

a contradiction. So at most one vertex of  $X$  is bad.

Call a pair  $I \subseteq X$  *bad* if  $L(I) \subseteq C_4$ ; otherwise  $I$  is *good*. Note that if  $I$  is good then  $I$  satisfies (1). By (3.18), (3.20), and  $u_3 = 0$ ,  $6(l - k + u_2) - 1 \leq \sigma_2 \leq 6(l - k + u_2)$ ; and so by (3.4), every pair  $I \subseteq X$  satisfies

$$l - k + u_2 - 1 \leq l(I) \leq l - k + u_2.$$

If the upper bound is sharp then call  $I$  *normal*; otherwise call  $I$  *abnormal*. Then there is at most one abnormal pair. If  $I$  is normal then  $l(\bar{I}) \leq l(I)$ ; so  $\Delta_1(I) \geq 0$ .

By (3.2), every triple  $T \subseteq X$  satisfies  $l(T) \leq u_2$ . If equality holds then call  $T$  *normal*; otherwise call  $T$  *abnormal*; if  $|L(T) \cap C_0| \leq u_2 - 2$  then call  $T$  *very abnormal*. Suppose two pairs  $I, J \subseteq T$  are both bad. At least one, say  $I$ , is normal. Then

$$(3.21) \quad 2(l - k) + u_2 \geq |C_4| \geq |L(I) \cup L(J)| \geq l - k + u_2 + l(J) - l(I \cup J)$$

$$l(I \cup J) \geq l(J) - l + k = \begin{cases} u_2 & \text{if } J \text{ is normal} \\ u_2 - 1 & \text{if } J \text{ is abnormal} \end{cases}.$$

So an abnormal triple contains at most one bad, normal pair, and a very abnormal triple contains at most one bad pair. A pair  $I$  contained in an abnormal triple satisfies  $\Delta_2(I) \geq 1$ .

Let  $J$  be a good, normal pair contained in a abnormal triple  $T$  with  $w \in X \setminus T$ . Then  $\Delta_1(J) + \Delta_2(J) \geq 1$ . So  $J$  satisfies (3) by (3.17). Also,

$$|W(v_J, v)| = l(J) + l(v) - l(J + v) \geq \begin{cases} 2l - k + u_2 - (u_2 - 1) = 2k & \text{if } v \in T \setminus J \\ 2l - k + u_2 - u_2 = 2k - 1 & \text{if } v = w \end{cases}.$$

So (\*)  $J$  satisfies (2), provided  $|W(v_J, w) \cup C_0| \geq 2k$ . In particular, (2) holds if  $w$  is good.

By (3.20) and (3.18),  $1 \leq \Delta_2(I) + \Delta_2(\bar{I}) \leq 2$ . As  $\sigma_3 = 4u_2 - \Delta_2(I) - \Delta_2(\bar{I})$ , we have  $4u_2 - 2 \leq \sigma_3(X) = 4u_2 - 1$ . In the first case there is one abnormal triple. In the second case, either there is a very abnormal triple or there are two abnormal triples.

First suppose there are two abnormal triples. Choose an abnormal triple  $T$  so that if there is a bad vertex then it is in  $T$ . As  $T$  contains three pairs and at most one is bad

and at most one is abnormal,  $T$  contains a good, normal pair  $J$ . Say  $J = yz$ ,  $T = xyz$ , and  $w \in X \setminus T$ . Then  $w$  is good, and thus  $J$  satisfies (2) by (\*).

Otherwise, let  $T = xyz$  be the only abnormal triple and  $w \in X \setminus T$ . There is at most one abnormal pair, and only if  $T$  is very abnormal. So  $T$  contains at most one bad pair. Now suppose  $T$  has two good, normal pairs  $xy$  and  $yz$ . By (\*), some  $J \in P := \{xy, yz\}$  satisfies (2), unless  $C_0 \subseteq L(J) \cup L(w)$  for both  $J \in P$ . Then, using  $u_1 = u_3 = r_3 = 0$ ,

$$l + u_2 = |C_0| \leq |L(xy) \cup L(w)| + |L(yz) \cup L(w)| - |L(xy) \cup L(yz) \cup L(w)|.$$

As  $T$  is abnormal, and both  $xy$  and  $yz$  are normal,

$$\begin{aligned} |L(xy) \cup L(yz) \cup L(w)| &= l(xy) + l(yz) + l(w) - l(xyw) - l(yzw) - l(xyz) \\ &\geq 3l - 2k + 2u_2 - (3u_2 - 1) = k + l - u_2. \end{aligned}$$

Combining the last two expressions yields the contradiction,

$$l + u_2 \leq |C_0| \leq 2(2k - 1) - (k + l - u_2) = 3k - 1 - l + u_2 - 1 = l + u_2 - 1.$$

Otherwise,  $T$  is very abnormal, and (say) both  $xz$  is bad and  $J = yz$  is normal. As  $T$  contains at most one bad pair,  $yz$  is also good. Since  $xz$  is bad,  $xz \subseteq C_0$ . Now

$$|C_0 \setminus W(\{v_J, w\})| \geq |L(xz) \setminus (L(w) \cup L(J))| \geq l - k + u_2 - (u_2 - 2) \geq 1,$$

and (2) holds by (\*), since  $\emptyset \neq L(xz) \setminus (L(w) \cup L(J)) \subseteq C_0$  implies

$$|W(\{v_J, w\} \cup C_0)| \geq |W(\{v_J, v\})| + 1 \geq 2k.$$

□

**Lemma 14.** *Suppose  $b = 1$  and  $X = xyzw \in \mathcal{U}_4$ . If*

$$|W(xyz)| \leq 2k + u_4 - 1 < |W(X)|$$

*then  $u_1 = 0$  and there exists a pair  $J \subseteq X$  such that:*

- (1)  $L(J) \not\subseteq C_4$ ;
- (2)  $|W(\{v_J, v\})| \geq 2k$  for  $v \in xyz \setminus J$  and  $|W(\{v_J, w\})| \geq 2k - 1 + u_3$ ; and
- (3)  $|W(\bar{J} + v_J)| \geq 2k + u_4$ .

*Proof.* Consider a pair  $vv' \subseteq xyz$ . Then

$$\begin{aligned} 2k + u_4 - 1 &\geq |W(xyz)| \geq |W(vv')| \geq l(v) + l(v') - l(vv') \\ &\geq 2l - (l - k + u_2 + u_3) \geq 3k - 1 - k + u_1 + u_4 \\ &\geq 2k + u_1 + u_4 - 1 \geq 2k. \end{aligned}$$

So  $u_1 = 0$ ,  $l(vv') = l - k + u_2 + u_3$ , and  $W(xyz) = W(vv')$ . Since  $vv'$  is arbitrary, every color in  $W(xyz)$  appears in at least two of the lists  $L(x)$ ,  $L(y)$ ,  $L(z)$ . So  $W(\{v_J, v\}) = W(xyz)$  and  $|W(\{v_J, v\})| \geq 2k$  for every pair  $J \subseteq xyz$  and vertex  $v \in xyz \setminus J$ . As  $|C_4| < 2k \leq |W(xyz)|$ , there is a pair  $J \subseteq xyz$  with  $L(J) \not\subseteq C_4$ . Furthermore,

$$|W(\{v_J, w\})| \geq l(J) + l(w) - l(J + w) \geq l - k + u_2 + u_3 + l - u_2 = 2k - 1 + u_3.$$

Finally, as  $W(\{v_J, v\}) = W(xyz)$  for  $v \in xyz \setminus J$ ,

$$|W(\bar{J} + v_J)| = |W(\{v_J, v\}) \cup W(w)| = |W(xyzw)| \geq 2k + u_4.$$

□

**Lemma 15.**  $G'$  is  $L$ -choosable.

*Proof.* First observe that if  $k$  is even then  $b = \dot{u} = \ddot{u} = \dot{r} = 0$  and  $H = G'$ . In this case the following argument is much simpler.

Using Hall's Theorem it suffices to show  $|S| \leq |W| := |\bigcup_{x \in S} L(x)|$  for every  $S \subseteq V(H)$ . Suppose for a contradiction that  $|S| > |W|$  for some  $S \subseteq V(H)$ . We consider several cases. Each case assumes the previous cases fail.

**Case 1:** There is  $X \in \mathcal{U}_4$  with  $|S \cap X| = 4$ . Then  $|W| < |S| \leq |G'|$ . By Lemma 13,  $b = 1$  and  $|G'| - 1 = |W(X)| < |S| = |G'|$ . So Step 11(a) is executed, and  $S = V(G')$ . In particular,  $\dot{X} \subseteq S$ . Thus

$$|S| \leq |H| = |G'| - 1 \leq |W(\bar{J} + v_J)| \leq |W(\dot{X})| \leq |W|.$$

**Case 2:** There exists  $Z = xyzw \in \mathcal{U}_3$  with  $|S \cap Z'| = 3$ . Now  $|S| \leq 3k - u_1 - u_2 - r_1 - r_2 - \dot{r}$ , since Case 1 fails. Say  $I_Z = xy$ . By Step 4,  $\Delta_1(xy) \geq 0$  and  $l(xyz) + l(xyw) = 2u_2 - \Delta_2(xy)$ . By Step 3,  $l(xyz) + l(xyw) \leq u_2 + r_1$ . So

$$\begin{aligned} (3.22) \quad |W| &\geq |W(Z')| \geq l(xy) + l(z) + l(w) - l(xyz) - l(xyw) - l(zw) \\ &= 2l + \Delta_1(xy) - 2u_2 + \Delta_2(xy) = 3k - b + \Delta_1(xy) - 2u_2 + \Delta_2(xy) \\ &\geq 3k - b + \Delta_1(xy) - u_2 - r_1 \geq |S| - b. \end{aligned}$$

As  $|S| > |W|$  equality holds throughout. Thus  $b = 1$ ,  $u_1 = r_2 = \dot{r} = \Delta_1(xy) = 0$ ,  $r_1 \leq u_2$ , and (\*)  $Y' \subseteq S$  for all  $Y \in \mathcal{R}_3$ . If  $u_4 = 0$  then

$$k = l - k + u_2 + u_3 \leq l(xy) = l(\overline{xy}) + \Delta_1(xy) = l(\overline{xy}).$$

By (3.1) this contradicts  $u_1 = 0$ . So  $u_4 \geq 1$ ,  $u_3 + u_4 \geq 2$ , and

$$r_1 + r_2 \leq u_2 + 0 = 2k - l - u_3 - u_4 \leq l - k - 1.$$

Thus  $r_3 \geq 1$ . Say  $Y \in \mathcal{R}_3$ . By (\*),  $Y' \subseteq S$ ; by (3.22),  $|W(Y')| \leq |W| = 3k - 1 - u_2 - r_1$ . So, using  $b = 1$  and  $u_1 = 0 = r_2$ , Step 11(b) is executed, and  $\dot{r} = 1$ , a contradiction.

**Case 3:** There exists  $X = wxyz \in \mathcal{R}_3$  with  $|S \cap X'| = 3$ . Say  $I_X = xy$ . Now  $|S| \leq 3k - u_1 - u_2 - u_3 - r_1 - r_2 - \dot{r}$ . By Step 7,  $l'(xy) \geq l'(wz)$ . By (3.3),  $N_3(X) \subseteq C_1 \subseteq C_2$ . So  $l'(xyz) = 0 = l'(xyw)$ . Set  $t = |C_2 \cap W|$ . Then  $t \leq u_2 + u_3 + r_1$ . So

$$\begin{aligned} |W| &= |W \setminus C_2| + |C_2 \cap W| \geq l'(xy) + l'(z) + l'(w) - l'(xyz) - l'(xyw) - l'(zw) + t \\ &\geq l'(xy) + l(z) - t + l(w) - t - l'(zw) + t \\ &\geq 3k - b - (u_2 + u_3 + r_1) \geq |S| - b. \end{aligned}$$

Thus  $b = 1$ ,  $0 = r_2 = u_1 = \dot{r}$ , and  $|W(X)| \leq |W| \leq 3k - 1 - u_2 - r_1$ . So Step 11(b) is executed, and  $\dot{r} = 1$ , a contradiction.

**Case 4:** There exists  $X \in \mathcal{U}_4$  with  $|S \cap X'| = 3$ . As the previous cases fail,  $|S| \leq 2k + u_4$ . Let  $xy \subseteq S \cap X' \setminus M$ . By (3.4),

$$\begin{aligned} |W| &\geq l(x) + l(y) - l(xy) \geq 3k - b - (l - k + u_2 + u_3) \\ &\geq 2k + (2k - l) - (u_2 + u_3) - b \geq 2k + u_1 + u_4 - b \geq |S| - b. \end{aligned}$$

So  $b = 1$ ,  $u_1 = 0$ ,  $|W| = 2k + u_4 - 1$ , and  $|S| = 2k + u_4$ . Thus  $S$  has exactly two vertices in every class of  $\mathcal{P}' \setminus \mathcal{U}'_4$  and exactly three vertices in every class of  $\mathcal{U}'_4$ . In particular,  $\dot{Z}' \subseteq S$ . If  $\dot{u} = 1$ , then  $\dot{X}' \subseteq S$  and  $|W(\dot{X}')| \geq |G'| - 1 \geq 2k + u_4 \geq |S|$  by Lemma 13; else  $|W(X)| \geq 2k + u_4$ . If  $\ddot{u} = 1$  then  $\ddot{X}' \subseteq S$  and  $|W| \geq |W(\ddot{X}')| \geq |S|$  by Lemma 14; else  $X = X'$ . As Step 11(c) is not executed,

$$|W| \geq |W((S \cap X) \cup \dot{Z})| \geq 2k + u_4 \geq |S|.$$

**Case 5:** There exists  $X \in \mathcal{U}_1$  with  $|S \cap X'| = 2$ . Say  $S \cap X' = \{v_I, v_{\bar{I}}\}$ . As the previous cases fail,  $|S| \leq 2k$ . Now

$$|W| \geq L(v_I) + L(v_{\bar{I}}) \geq 2k \geq |S|.$$

**Case 6:** There exists  $X \in \mathcal{U}_3$  with  $|S \cap X'| = 2$ . Say  $S \cap X' = vv'$ . As the previous cases fail,  $|S| \leq 2k - u_1$ . If  $v, v' \notin M$  then  $\bar{I}_X = vv'$ . By (3.1),  $l(\bar{I}_X) \leq k - 1$ . So

$$|W(vv')| \geq l(v) + l(v') - l(vv') \geq 2l - (k - 1) \geq 2k \geq |S|.$$

Otherwise  $v = v_{xy}$ , where  $I_X = xy$ , and  $v' = z \notin M$ . Then

$$\begin{aligned} |W(vv')| &\geq l(v_{xy}) + l(z) - l(xy + z) \\ &\geq l - k + u_2 + u_3 + l - u_2 \geq 2k - b + u_3 \geq 2k \geq |S|. \end{aligned}$$

**Case 7:** There exists  $X \in \mathcal{U}_4$  with  $|S \cap X'| = 2$ . Say  $S \cap X' = vv'$ . If possible, choose  $X$  so that  $S \cap X' \cap M = \emptyset$ . As the previous cases fail,  $|S| \leq 2k - u_1 - u_3$ . If  $v, v' \notin M$  then

$$\begin{aligned} |W(vv')| &= l(v) + l(v') - l(vv') \geq 2l - (l - k + u_2 + u_3) \\ (3.23) \quad &\geq 2k - b + u_1 + u_4 \geq 2k \geq |S|. \end{aligned}$$

Else  $b = 1$ , and (say)  $v \in M$ . By Step 11,  $v = v_j$  or  $v = v_{\bar{j}}$ , and  $u_1 = 0$ .

If  $v = v_j$  then Step 11(a) was executed. So (i)  $r_3 = 0$ , (ii)  $|W(vv')| \geq 2k - 1$ , and (iii) if  $|W(vv')| = 2k - 1$  then  $u_2 \geq 1$  and  $|W(vv' \cup \dot{Z}') \cup C_4| \geq 2k$ . Since

$$2k \geq |S| > |W| \geq |W(vv')| \geq 2k - 1,$$

$|S| = 2k$ . Thus  $S$  contains exactly two vertices of each part  $Y' \in \mathcal{P}'$ . In particular,  $\dot{Z}' \subseteq S$ . The choice of  $X$  implies  $u_3 = 0$  and  $u_4 = 1$ ; thus  $u_2 = l - k \geq 1$ . Since  $u_3 = 0 = r_3$ ,  $M_4 \subseteq S$ . So  $|W| \geq |W(vv' \cup \dot{Z}') \cup C_4| \geq 2k$ , a contradiction.

Otherwise  $x = v_{\bar{j}}$ . Then Step 11(c) was executed. So there is a part  $\ddot{X} = xyzw \in \mathcal{U}_4$  with  $\ddot{I} = xy$  such that

$$|W(xyz \cup \dot{Z})| \leq 2k + u_4 - 1 < |W(\ddot{X})|,$$

$|W(\{v_{xy}, w\})| \geq 2k - 1 + u_3$ , and  $|W(\{v_{xy}, z\})| \geq 2k$ . So we are done, unless  $v' = w$  and

$$2k \geq |S| > |W(\{v_{xy}, w\})| \geq 2k - 1 + u_3.$$

Thus  $u_3 = 0$  and  $|S| = 2k$ . So  $S$  contains exactly two vertices of each class  $Y' \in \mathcal{P}'$ . In particular,  $\dot{Z}' \subseteq S$ . As  $|W(\ddot{X})| > |W(xyz \cup \dot{Z})|$ , we have  $|L(w) \setminus W(xyz \cup \dot{Z}')| \geq 1$ . So

$$|W| \geq |W(\{v_{xy}, w\} \cup \dot{Z}')| \geq W(\dot{Z}') + 1 = l + u_2 + 1 = 2l - k + 1 = 2k.$$

**Case 8:** There exists  $X = xyzw \in \mathcal{U}_2$  with  $|S \cap X'| = 2$ . Say  $S \cap X' = \{v_I, w\}$ . As the previous cases fail,  $|S| \leq 2k - u_1 - u_3 - u_4 = l + u_2$ . Since  $L(xyz) \cap L(w) = \emptyset$ , we have

$$|W| \geq |W(X')| \geq l(xyz) + l(w) \geq u_2 + l \geq |S|.$$

**Case 9:** Otherwise. As the previous cases fail,

$$|S| \leq u_1 + u_2 + u_3 + u_4 + 2|\mathcal{R}| = l.$$

As  $\mathcal{L}(M)$  has an SDR, there is a vertex  $x \in S \setminus M$ . Thus  $|W| \geq l(x) = l \geq |S|$ . □

We are done. □

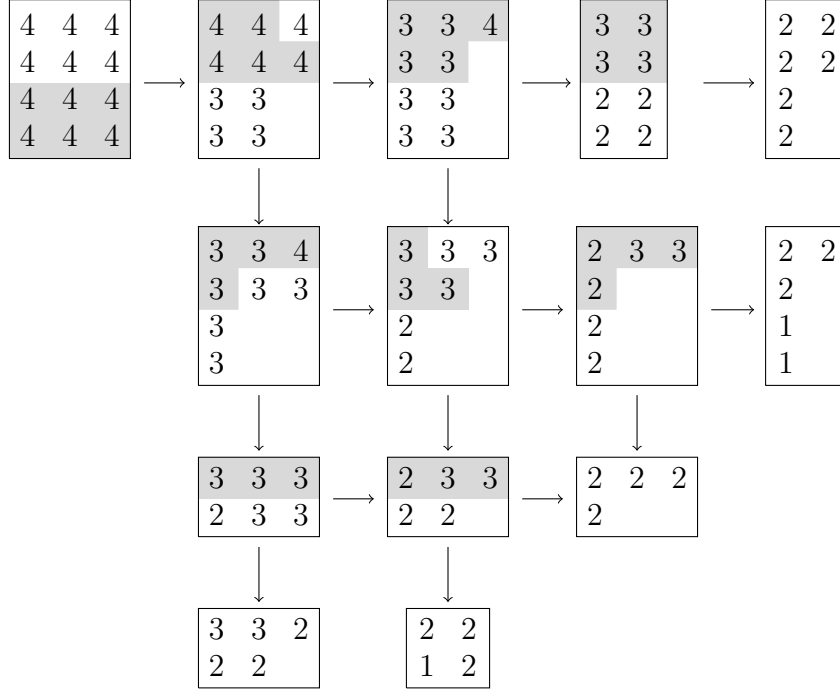


FIGURE 4.1. Strategy for Alice demonstrating  $\text{ch}^{OL}(K_{4*3}) \geq 5$ .

#### 4. ON-LINE CHOOSABILITY

By Theorem 7,  $\text{ch}(K_{4*3}) = 4$ . Using a computer we have checked that  $\text{ch}^{OL}(K_{4*3}) = 5$ , but do not have a readable argument to verify the upper bound. Here we prove the lower bound.

**Theorem 16.**  $\text{ch}^{OL}(K_{4*3}) \geq 5$ .

*Proof.* Figure 4.1 describes a strategy for Alice. The top left matrix depicts the initial game position, and Alice's first move. The positions in the matrix correspond to the vertices of  $K_{4*3}$  arranged so that vertices in the same part correspond to positions in the same column. The order of vertices within a column is irrelevant, as is the order of the columns. The numbers represent the size of the list of each corresponding vertex. The sequence of numbers represents a function  $f$ . The shaded positions represent the vertices that Alice presents on here first move.

As play progresses Bob chooses certain vertices presented by Alice and passes over others. When a vertex is chosen its position is removed from the next matrix (and the positions in its column of the remaining vertices and the order of the columns may be rearranged). When he passes over a vertex its list size is decreased by one (and its position in its column and the order of the columns may change). The arrows between the matrices point to the possible new game positions that arise from Bob's choice, not counting equivalent positions and omitting clearly inferior positions for Bob. In particular we assume Bob always chooses a maximal independent set.

For example, after Bob's first move there is only one possible game position, provided Bob chooses a maximal independent set. It is shown in the second column of the first row, along with Alice's second move. Now Bob has two possible responses that are pointed to by two arrows. Also consider the matrix in the third row and third column. There are three nonequivalent responses for Bob, but choosing the offered vertex in the second

column of the matrix results in a position that is inferior to choosing the offered vertex in the first column. So this option is not shown.

Eventually, Alice forces one of five positions  $(G, f)$  such that  $G$  is not  $f$ -choosable, and Bob, being a gentleman, resigns.  $\square$

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